A Survey of Application of Digital Computers to General Circuit Analysis

Submitted to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Office of Grants and Research Contracts

Washington D. C. 20546

This work was done under the NASA grant NGR-39-023-004, at the Electrical Engineering Department, Villanova University Villanova, Pennsylvania.

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ABSTRACT

The purpose of this paper is to survey the latest developments in the application of digital computers to circuit analysis and design.

In recent years there is a rising awareness of digital computers as a potential tool for engineering design in general and for circuit analysis and synthesis in particular. Whether they are used to carry out iterative computation in the design process, or to resort to some statistical techniques in variability study, or to process from topological input to graphic output automatically, the horizon of realizing a true man-machine team in engineering is broadening rapidly. In the text advances in methodology of using computer for general circuit analysis and design will be discussed; typical computer programs will be reviewed; typical applications will be given; and some of the areas to be heeded in contribution toward future progress will be indicated.

* This work was supported by the National Aeronautics and Space Administration under the Grant No. 39-023-004.

I. INTRODUCTION

There are many convincing instances of symbiosis in the development of computer technology as it is today. For example, the invention of transistors make the general purpose digital computer truly large scale in mathematical and logical operations and still manageable in its physical and electrical construction. In turn it is mainly the wide use of transistors in computers that kindled the imagination of the semiconductor product industry. If we were to remain in the confine of vacuum tube circuit world, the ceiling of computer capabilities would be lower than we have attained at present; if it were not for satisfying the stringent and high speed requirements in computer applications, the transistor would not enjoy such a highly serviceable reputation everywhere. The electrical engineers have designed and delivered electronic computers for twenty years. It seems high time for circuit designers to be benefited by computers in a nontrivial way. By the use of digital computers in circuit analysis better designs can be attempted in the reduced temporal and monetary scale. Through more elaborate design of circuits the computer may come closer to the desired size, speed and reliability.

The initial applications of computer to circuit analysis arises from the need of the computer itself. Digital circuits require that a number of tolerance conditions and performance requirements be met at one time. A circuit may be deceivingly simple in classroom discussion of its principle of operation and quite involved in actual design to make it function properly under most adverse conditions. The design of these circuits can be materially aided by using a digital computer to solve the mathematical equations with the required degree of accuracy and sustained enthusiasm in monotonous iterations [16]. As the circuit grows in complexity it becomes impractical if not impossible to write out explicitly the effect of one circuit parameter upon another.

Where the laboratory testing used to be the only resort, digital simulation can be utilized to great advantage in shortening the time lag between performance of experiments in laboratories on the one hand and analysis of data by design engineers on the other [27]. Besides, over-rating studies can be made without physically damaging the expensive circuit elements and measurements can be made with no particular preference to localities or measuring instruments [18]. More recently the digital computers are introduced into the role of a faithful assistant in automated engineering design. In the area of circuit analysis and design, the whole process from writing equations to the display of output waveforms can be programmed and carried out on the computer. This is demonstrated at the Electronics Systems Laboratory of Massachusetts Institute of Technology [11].

II. ANALYSIS VS SYNTHESIS

For a given configuration of network and time function of excitation the determination of the network response is defined as analysis. When the excitation and the response are given and it is required to determine a network, the problem is defined as synthesis [32]. Generally, in analysis there is a unique solution although it may be difficult to find. In synthesis, however, solutions are not unique and there may exist no solution at all. A choice must be made among possible solutions according to accepted criterion. This is one of the general characteristics of engineering design in the area where digital computer can lend considerable assistance.

In the circuit analysis problem, computer programs can be prepared when the method of analysis is chosen: nodal or mesh equations, frequency or time domain analysis, representation of nonlinear circuit elements by terminal characteristics or physical models, etc. They may be intended either for a special type of circuit or for a general class of networks. In the circuit synthesis problem, specific programs are usually generated for specific purposes. Therefore all available computer programs for circuit analysis and design can be classified into two categories: those dealing with the general type of circuit configurations with a liberal set of constraints and those tailored for a special type of network, or a special technique of analysis or synthesis, or a particular design problem.

Some of the features of a generalized circuit analysis program will be illustrated in Section III. To show the variety and spectrum of special programs in the literature we may mention the work done Calahan [7] in which a complete solution is outlined for generating networks equivalent to a given network while forcing certain elements to pre-selected values. Mayeda and Seshu [20] present a procedure of listing all trees in a network without duplications. Logic circuit synthesis has been treated by Dertouzos and Santos [10]; random access communication networks by Amara [1] and Bedrosian [3]. Yamamoto, Fujimoto and Watanabe [33] present a computer program for the frequency transformation of a low-pass filter to a band-pass filter with a minimum number of inductances. The program for the precise analysis of a parametric amplifier consisting of a single time-varying capacitance imbedded in a fixed parameter network is given by Leon and Bean in [17].

III. PROGRAMS DESCRIPTION

The requirements of a computer program for general circuit analysis has been articulately stated by Kuo [15]. It would be a luxurious idea to demand all the desirable features embraced in one single program. However, they can be summarized and itemized for discussion and trade-off considerations. Five general programs are used for illustration, namely,

ASAP	[14],	Automated Statistical Analysis Program;
CIRCS	[12],	linear CIRCuit analysis System;
ECAP	[13],	Electronic Circuit Analysis Program;
NET-1	[18],	NETwork analysis program;
STANPAK	[8],	Statistical Tolerance ANalysis PacKage.

(1) Equation Writing. Circuit analysis always starts with establishing algebraic or integro-differential equations for the given circuit with the knowledge of some physical laws. It is then followed by the solution of the equations and interpretation of the results. The very first step of setting up KCL or KVL simultaneous equations has been successfully mechanized in CIRCS, ECAP, ASAP, and NET-1. The program user, i.e. the electrical engineer in this case, must translate circuit information from the ordinary schematic diagram into serial, topological description in accordance with certain format specified by the program. As this node-to-node data are fed in as input, the program will establish corresponding connection matrices and immittance matrices [4, 5] and perform appropriate mathematical manipulations.

(2) Parameter Values. In addition to the nominal values of each parameter, tolerances may be inserted either in terms of percentage of the nominal value as in ASAP, or max/min values as in CIRCS, ECAP, and STANPAK. The range of time or frequency or supply voltage over which the analysis is to be performed will be given by two extreme values and the incremental interval size. In CIRCS there are three possible frequency specifications: a single value of frequency, lower and upper limits for a set of frequencies which may be incremented by adding a constant value Δf to each successive increment in the frequency or by multiplying each successive value for the frequency by a constant k. In CIRCS and ECAP both current source and voltage source are allowed in the analysis. In ASAP and NET-1 only voltage sources can be recognized; current sources may be described to the computer by converting them into voltage sources as prescribed by conventional network theory.

(3) Diode and Transistor Representation. CIRCS and ECAP both use linearized equivalent circuit which is valid for the range of operation decided by the circuit designer. Dependent current sources, either voltage - or current-controlled, can be accomodated by the program and they are specified by three numbers: the controlling parameter, the controlled branch, and the proportionality factor which corresponds to the value of transconductance or current gain as the case may be. The various regions of operation (off/on for diodes, off/active/saturation for transistors) are made possible through the program switch. Actuation of the switch depends upon the current direction in the controlling branch. A number of branch parameters can be caused to assume their respective alternate values upon the change of the state of the switch.

ASAP has an entirely different scheme and it requires that the terminal characteristics of the nonlinear circuit element be given in terms of the breakpoints of a piecewise linear approximation curve. The program forms the equivalent circuit and applies an iterative procedure to find the operating point automatically. For the V-I curve of a diode as many as twenty points can be used for one curve; two curves (upper and lower tolerance limit curves) per diode type and five different diode types are allowed in the circuit for analysis. The breakpoints of the adjacent segments do not need to be spaced uniformly. The user can space the points closely near the operating point and obtain better accuracy. For transistors there are two models available. The simpler model gives adequate representation in the active and cutoff regions of operation but inadequate for saturated region. An exact model will be used instead. One set of curves, emitter current I_e vs base-emitter voltage V_{be}, is sufficient for the first simple model, while two sets of curve data are necessary for the second exact model —— I_b vs V_{be} and I_c vs V_{ce}. Because ASAP is designed for d-c statistical analysis, only resistance and controlled current source are considered in the models of diode and transistor.

NET-1 employs subroutines to handle the nonlinear elements. The user has to only state the type name of the diode, e.g. 1N661, or the transistor, e.g. 2N398, and nodes of connection of the element in the circuit. A library of parameter values stored on magnetic tape or disc file will be called in by the program in analysis. Ebers-Moll a-c model of transistors is used exclusively. Facilities are available for adding new type of nonlinear elements to the library tape.

(4) D-C, A-C, Transient Analysis. As CIRCS, ECAP and ASAP are the offspring of the same lineage, they share strong similarities in input format, output variables, and option of analysis for request. All three programs will produce a complete listing of nodal voltages and branch currents throughout the circuit. ASAP treats d-c circuit only, CIRS and ECAP provide the choice of d-c, a-c and transient analysis. NET-1 furnishes d-c and transient solution and calculate total power dissipation in addition to voltage and current. CIRCS and ECAP assume the units ampere, volt, ohm, farad, henry, second, and cps: NET-1 uses milliampere, volt, kilohm, picofarad, millihenry, nanosecond and milliwatt. Although alternate sets of self-consistent units may be employed, it must be kept in mind that the circuit element values which the program occasionally introduces into the circuit (for example, a small number for short circuit) should not lose its intended significance with the alternate set of units.

In the transient analysis portion of any general circuit analysis program the specification of the time increment of calculation and the finish time are at the user's discretion. The print-out interval may be set equal to one or more of the time step of calculation. Time-dependent sources are recognized by the ECAP in tabular form.

NET-1 classifies signal sources into five classes: pulses, tabular pulses, sine waves, amplitude-modulated sine waves, and decaying exponentials. By a combination of two basic classes of signals many other waveforms can be simulated.

(5) Sensitivity, Worst Case, and Statistical Calculations.

When there is provision for parameter modification in the program, as in ECAP and ASAP, some of these calculations will become the additional features which can give the designer a clearer insight in the design procedure. The sensitivity study consists of finding the relative effect of variations in the circuit elements on the output parameters. The worst case analysis yields the maximum and minimum variations of the output parameters when the worst possible combination of circuit element tolerances occurs. In the so-called Mandex (Modified AND EXpanded) worst case analysis the assumption is made that there is not just one possible worst case condition for a circuit, but one for each output variable; therefore, a complete worst case analysis is performed on each output variable.

The extent to which statistical analysis is carried out varies greatly with the program. In ECAP the circuit element values are assumed to be statistically independent and normally distributed about their nominal values. The standard deviation of each output parameter is computed. In ASAP, which aims at a more elaborate statistical study, each circuit element may have any given shape of distribution, uniform, normal, or of any other specified curve. Using the Monte Carlo random sampling technique, data for plotting the histograms of the output parameters are prepared. In STANPAK the program is written not only for computing the mean and variance for each independent variable, the mean, variance and tolerance limits for the dependent variable, but also for relaxing or tightening component tolerances until a predetermined tolerance of the dependent variable is satisfied. The drawback in the present version of the program stems from the fact that the relaxation or tightening process continues equally and simultaneously at both maximum and minimum values as long as either end is not within the prescribed limit. This means that one extreme may be overdone before the other limit is met.

(6) Machine Configuration and Circuit Size Limitations.

STANPAK requires an 8-k memory associated with the main computer such as GE 225. Seven functions can be handled satisfactorily by the program.

ECAP was first developed for the use on the 40-k IBM 1620 Data Processing System with one IBM 1131 Disc Storage Drive. The maximum allowable circuit size is given in Table I.

Table I

Circuit Limitations for ECAP

	d-c	a-c	trans.
nodes	20	20	20
branches	60	60	60
mutual induct.		5	
volt/cur sources			
fixed	60	60	60
time-depend.			5
dep. cur sources	10	10	10
switches			20

An IBM 7090/94 version of the ECAP has been made available since then.

ASAP is to be run on the IBM 7090 and has the limitations on d-c circuits as given in Table II.

Table II

Circuit Limitations for ASAP

nodes	50	
diodes + transistors	40	
different diode curves	5	
transistor curves	3	
distribution curves	5	(other than uniform)
input parameter	75	
output parameter	25	

NET-1 which is also written for the IBM 7090 has the analysis capability as depicted in Table III.

Table III

Circuit Limitations for NET-1

R, C	400 each
L	400 with no mutual coupling
	300 with mutual coupling
transistors	40
diodes	75
volt. source	
fixed	63
time-depend.	63

IV. TYPICAL APPLICATIONS

Some of the applications of the computer-aided general circuit analysis at the present level of accomplishment can be found in the design of MINUTEMAN guidance and control systems [27] and in the development of the MARINER C command subsystems [23, 30]. It is the high reliability premium demanded by spacecraft systems that gives a commanding call to the digital computer as a circuit design tool. Variations of all parameter over their maximum ranges must include the effects of environment, aging and production deviations; and the output information must have d-c performance e.g. operating-point stability, load capability, and transient performance, e.g. charge and discharge time constants, turn-on and turn-off charge requirements, available and required trigger energy. These myriad tedious and time-consuming calculations are all relegated to the computer so that deadline of design review can be satisfactorily met with confidence. The ASAP which is developed by the International Business Machines Corp. under a contract with the Goddard Flight Center of National Aeronautics and Space Administration is another example most helpful for reliability studies of electronic circuits.

In the time-sharing computing system, as one sits in front of the console and draws a schematic up to 8 nodes and 12 branches, the linear circuit is analyzed on line and the output waveform appears as the cathode-ray oscilloscope display within a few seconds. This has been accomplished at the Electronic Systems Laboratory of Massachusetts Institute of Technology for some time [11]. The extensive storage required by the program is made possible through the community utility concept of a computing system.

Two digital computer analysis programs were put into operation at the IBM Space Guidance Center at Owego, N.Y., under the sponsorship of the Air Force to study the circuit response in a pulsed nuclear radiation environment [9]. One program requires linear d-c equations be written manually and then programmed for computer solution. The other program generates the equations from topological circuit information and then solves the equations during the radiation burst automatically.

The above examples show a few typical cases of computer-aided circuit analysis and design. There are many other significant work done at ARINC Corp. [19] and at Norden Division of United Aircraft Corp. [24].

V. CONCLUDING REMARKS

1. Network theory has been recognized as a well established discipline. It is firmly rooted and there is plenty room for new branches. In attempting to obtain the fullest services a computer is capable of, new digital techniques based on the existing wealth of network theory must be diligently explored by the circuit designer. Time-domain solutions of electric circuits are possible in many programs today, but they are admittedly somewhat clumsy and slow. The latest effort by Stineman [29], Miles [22] and Branin [6] merit our earnest attention.

2. The usefulness of a circuit analysis program would be much enhanced if parameter modification can be made conveniently and results can be brought out quickly. New approaches other than the usual node or mesh equations may be devised. Pottle's state-space implementation on a digital computer [26] and So's hybrid matrix formulation [28] point to some of the possibilities.

3. The development of a comprehensive program for general circuit analysis takes many man hours. It is part of the growing process and only experience can improve our undertaking of any kind. It might be remembered that generalized analysis is not the only program for all purposes. For example, an integrated circuit may be represented by a ladder structure [2] with a number of sections. The technique developed by Pacello [25] would be very powerful and fit moderately sized computers nicely. Both general and special analysis have their respective places in computer applications.

4. Along the trail of computer applications to physical and life sciences we were first so hopeful and dreamful about its future that the similes like giant brain or electronic brain has been suggested. In the process of maturity through age, we begin to feel the corners and realize the limitations of the computer as we

find it more and more useful. The ideal man-machine symbiosis in engineering design will result a direct and harmonious partnership between them. The role of the computer in circuit analysis and synthesis will grow in importance. However, the creative part of the activity must originate from the designer in structuring, evaluating, and modifying the program. The final design product reflects nobody else but the imagination and ingenuity of the design engineer.

A relatively few years ago, 90 per cent of the experiments done at one of the leading scientific laboratories in the country, the Bell Telephone Laboratories, were performed in actual laboratories and only 10 per cent were done on computers. Probably before 1970 the situation will be reversed [31]. When the day comes that the computer provides its user "with logical tools to aid him in his intellectual work just as electric tools to aid him in his physical work" [21], we electrical engineers had better be prepared for it.

REFERENCES

(1) R. C. Amara, "Computer Design and Control of Probabilistic Communication Networks", IRE Trans. on Communication Systems, vol. CS-11, pp. 30-35; March, 1963.

(2) A. G. Atwood and L. C. Drew, "Computer Analysis of an Integrated Circuit Amplifier", RCA Engineer, vol. 10, no. 3, pp. 27-29; October/November, 1964.

(3) S. D. Bedrosian, "Finding the Maximum Complete Subgraph in Coding Models for Random Access Communications", IEEE Internat'l Conv. Record, vol. 14, pp. 250-253; 1966.

(4) F. H. Branin, Jr., "D-C and Transient Analysis of Networks Using a Digital Computer", IRE Conv. Record vol. 10, pt. 2, pp. 236-256; 1962.

(5) ______________, "Machine Analysis of Networks and Its Application", IBM Tech. Rept. TR 00.855; March 30, 1962.

(6) ______________, "A New Method for Steady-State A-C Analysis of RLC Networks", IEEE Internat'l. Conv. Record vol. 14, pt. 7, pp. 218-223; 1966.

(7) D. A. Calahan, "Computer Generation of Equivalent Networks", IEEE Conv. Record, vol. 12, pt. 1, pp. 330-337; 1964.

(8) C. A. Combs, Jr., "Stanpak, GET Program Abstract", General Electric Co., Phoenix, Ariz.: November, 1965.

(9) W. E. Craig and H. W. Mathers, Digital Computer Techniques for Determining Circuit Behavior in a Pulsed Nuclear Environment", IEEE Trans. on Nuclear Science, vol. NS-10, pp. 168-175; November, 1963.

(10) M. L. Dertouzos and P. J. Santos, Jr., "CADD: On-Line Synthesis of Logic Circuits", Report ESL-R-253, MIT Project DSR 9948; Electronic Systems Laboratory, Mass. Inst. Tech., December, 1965.

(11) ______________, and J. F. Reintjes, "Computer-Aided Electronic Circuit Design", Project MAC Progress Report II, pp. 81-87; Mass. Inst. Tech., July, 1965. AD 629 494.

(12) J. N. Hatfield, "A Linear Circuit Analysis Program for the IBM 1620/1311 20k Data Processing System (CIRCS)", Jet Propulsion Lab. Pasadena, Calif.: May, 1964.

(13) International Business Machines Corp., "1620 Electronic Circuit Analysis Program (ECAP 1620-EE-02)", IBM, Tech. Publ. Dept., White Plains, N. Y.; 1965.

(14) _______________, "ASAP, An Automated Statistical Analysis Program", Techn Rept. prepared for Goddard Space Flight Center, Greenbelt, Md., Contract No. NAS 5-3373, 1963.

(15) F. F. Kuo, "Network Analysis by Digital Computer", Proc. IEEE, vol. 54, pp. 820-829; June, 1966.

(16) G. H. Leichner, "Network Synthesis Using a Digital Computer", J. Assoc. Computing Mach., vol. 4, pp. 143-147; April, 1957.

(17) B. J. Leon and C. A. Bean, "Analysis and Design of Parametric Amplifiers with the Aid of a 709 Computer", IRE Trans. on Circuit Theory, vol. CT-8, pp. 210-215; September, 1961.

(18) A. F. Malmberg, F. L. Cornwell and F. N. Hofer, "NET-1 Network Analysis Program, 7090/94 Version", Report No. LA-3119, Los Alamos Scientific Laboratory, August, 1964.

(19) R. A. Mammano, K. D. Pope and E. P. Schneider, "Computer-Assisted Circuit Analysis", EDN vol. 10, no. 14, pp. 132-139; November, 1965.

(20) W. Mayeda and S. Seshu, "Generation of Trees Without Duplication", IEEE Trans. on Circuit Theory, vol. CT-12, pp. 181-185; June, 1965.

(21) J. McCarthy, "Time-Sharing Computer Systems", collected in Management and the Computer of the Future, edited by M. Greenberger, M.I.T. Press, 1962.

(22) R. S. Miles, "Transient Response using Matrizant Procedures", Proceedings 2nd Design Aids Symposium, Autonetics, Anheim, Calif., Pub. No. 558-A-14, paper No. IV; September, 1963.

(23) Motorola Inc., Western Center Military Electronics Division, "Final Report of WE-2937-1 of the Mariner C Circuit Design Review", June, 1964.

(24) Norden Division, United Aircraft Corp., "Development of Techniques for Automatic Manufacturing of Integral Circuits", in two volumes, Tech. Rept. AFML-TR-65-386; Norden, Norwalk, Conn.; November, 1965.

(25) E. A. Pacello, "The Use of 'Deuce' for Network Analysis", The Marconi Review, vol. 24, no. 142, Third Quarter; 1961.

(26) C. Pottle, "On the Partial Fraction Expansion of a Rational Function with Multiple Poles by Digital Computer", IEEE Trans. on Circuit Theory, vol. CT-11, pp. 161-162; March, 1964.

(27) H. S. Scheffler and F. R. Terry, "Description and Comparison of Five Computer Methods of Circuit Analysis", Proc. 6th Symposium on Ballistic Missiles and Aerospace Technology, Los Angeles, 1961, Ed. by C. T. Morrow, L. D. Ely and M. R. Smith, Academic Press, 1961.

(28) H. C. So, "Analysis and Design of Linear Networks with Variable Parameters Using On-Line Simulation", Proc. of 3rd Allerton Conf. on Circuit and System Theory; pp. 634-646; October, 1965.

(29) R. W. Stineman, "Digital Time-Domain Analysis of Systems with Widely Separated Poles", J. of Assoc. Computing Machinery, vol. 12, pp. 286-293; April, 1965.

(30) Texas Instruments Inc., "Worst Case Analysis for Mariner C Encoder", August, 1963.

(31) S. Thomas, "Computers", (book) Holt, Rinehart and Winston Inc. New York, N. Y., 1965.

(32) M. E. Van Valkenburg, "Introduction to Modern Network Synthesis", (book) John Wiley and Sons, Inc. New York, N. Y., 1960.

(33) K. Yamanoto, K. Fujimoto and H. Watanabe, "Programming the Minimum Inductance Transformation", IRE Trans. Circuit Theory, vol. CT-3, pp. 184-191; September, 1961.